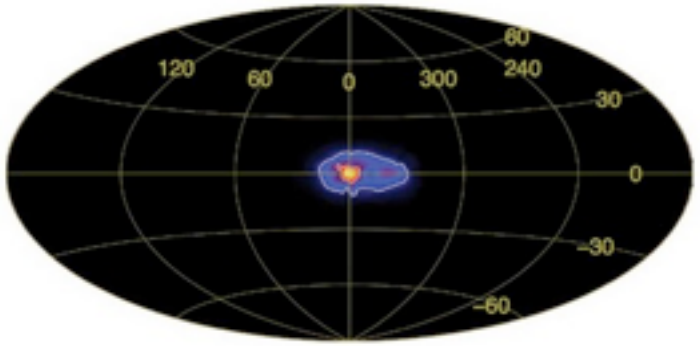
Dark Z
(in comparison to Dark Photon)

based on several works with H. Davoudiasl, I. Lewis, W. Marciano, and M. Sher
(arXiv:1203.2947, 1205.2709, 1303.6653, 1304.4935)

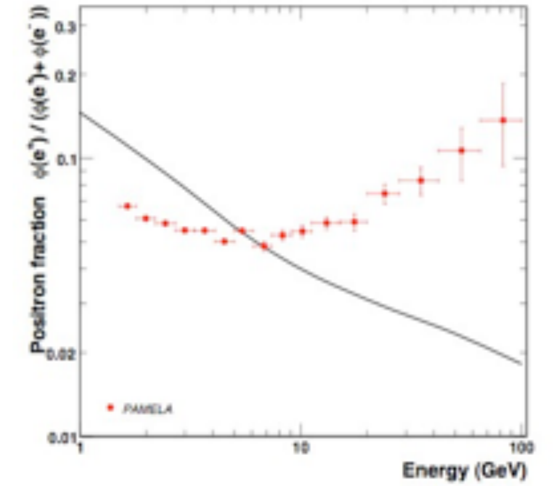
Hye-Sung Lee
(William and Mary / JLab)

Brookhaven Forum 2013
May 2013

Prelude



Dark Force
(New gauge interaction in Dark sector)



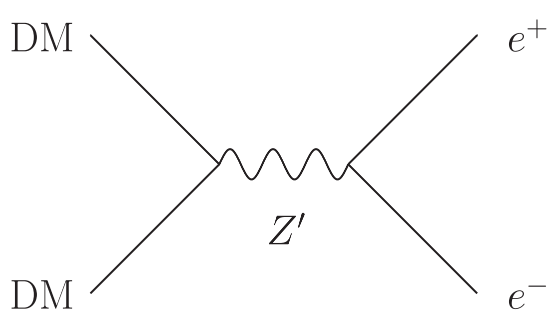
Dark Force carrier: Light Z' [a new gauge boson of $m_{Z'} \sim O(1)$ GeV] with suppressed couplings

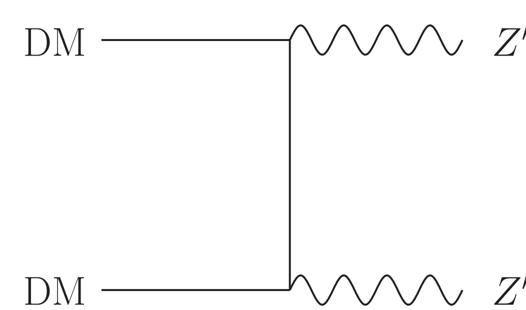
(Topic discussed in some talks in this workshop: Carone, Schuster, Spray, ...)

DM annihilation at Galactic center with "GeV-scale gauge boson" can explain

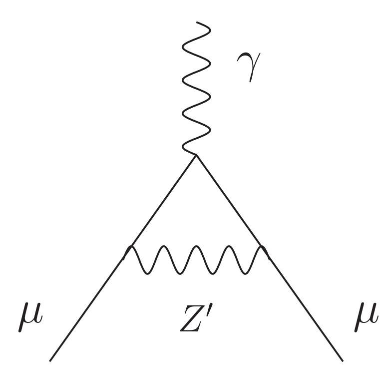
(1) 511 keV gamma-ray (INTEGRAL) [Fayet (2004)]

(2) Positron excess (ATIC, PAMELA) [Arkani-Hamed,Finkbeiner,Slatyer,Weiner (2008)]





Also, $g_\mu - 2$ anomaly (3.6σ) can be explained [Fayet (2007); Pospelov (2008)].



$$(\text{magnetic moment}) = -\frac{g\mu_B S}{\hbar}$$

Outline

Many searches of this new fundamental force (Dark Force) are actively going on especially at Low-Energy experimental facilities (such as JLab in Virginia).

In this talk,
(i) We generalize the "Dark Photon" to "Dark Z".
(ii) We expand the relevant Dark Force search experiments.

1. Overview of Dark Photon (well-established benchmark model)

2. Dark Z (model with H. Davoudiasl and W. Marciano)

3. Dark Z Implications for Parity-Violating Experiments

4. Dark Z Implications for Rare Meson/Higgs Decays

1. Overview of Dark Photon

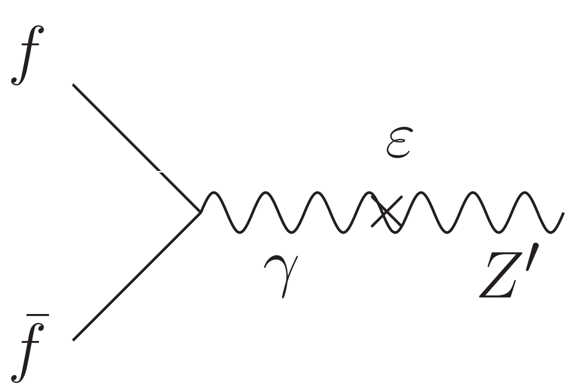
Dark Photon

Consider a U(1)’ gauge symmetry - Dark U(1) - under which the SM particles have “zero” charges.

Z’ couples to SM particles through kinetic mixing of $U(1)_Y$ & U(1)’. [Holdom (1986)]

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z'^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

Typical phenomenology of the $U(1)_Y$ & U(1)’ kinetic mixing is carried out in the setup that Z’ couples only to EM Current just like Photon (→ Dark Photon).



$: \ \varepsilon\, eQ_f$

$$\mathcal{L}_{\rm int} = -\varepsilon\, eJ^{\mu}_{em}Z'_{\mu}$$

Photon-Z’ mixing

(coupling) = ε (Photon coupling)

Puzzling at first glance since the kinetic mixing is B-Z’ mixing.

$B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$ (What happened to Z-Z’ mixing?)

Higgs structure matters

Dark Photon is justified **in the simplest Higgs sector**

"SM Higgs doublet + Higgs singlet"

(Higgs singlet: to give mass to Z').

Z-Z' kinetic mixing is cancelled by Z-Z' mass mixing (which is "induced by kinetic mixing") at Leading order.

$$\mathcal{L}_{\text{int}} \sim -eJ^{\mu}_{em}A_{\mu} - (g/\cos\theta_W)J^{\mu}_{NC}Z_{\mu}$$

(Kinetic mixing diagonalization) $\rightarrow -eJ^{\mu}_{em}[A_{\mu} + \varepsilon Z'_{\mu}] - (g/\cos\theta_W)J^{\mu}_{NC}[Z_{\mu} + O(\varepsilon)Z'_{\mu}]$

(Z-Z' mass matrix diagonalization) $\rightarrow -eJ^{\mu}_{em}[A_{\mu} + \varepsilon Z'_{\mu}] - (g/\cos\theta_W)J^{\mu}_{NC}Z_{\mu}$

depends on Higgs sector

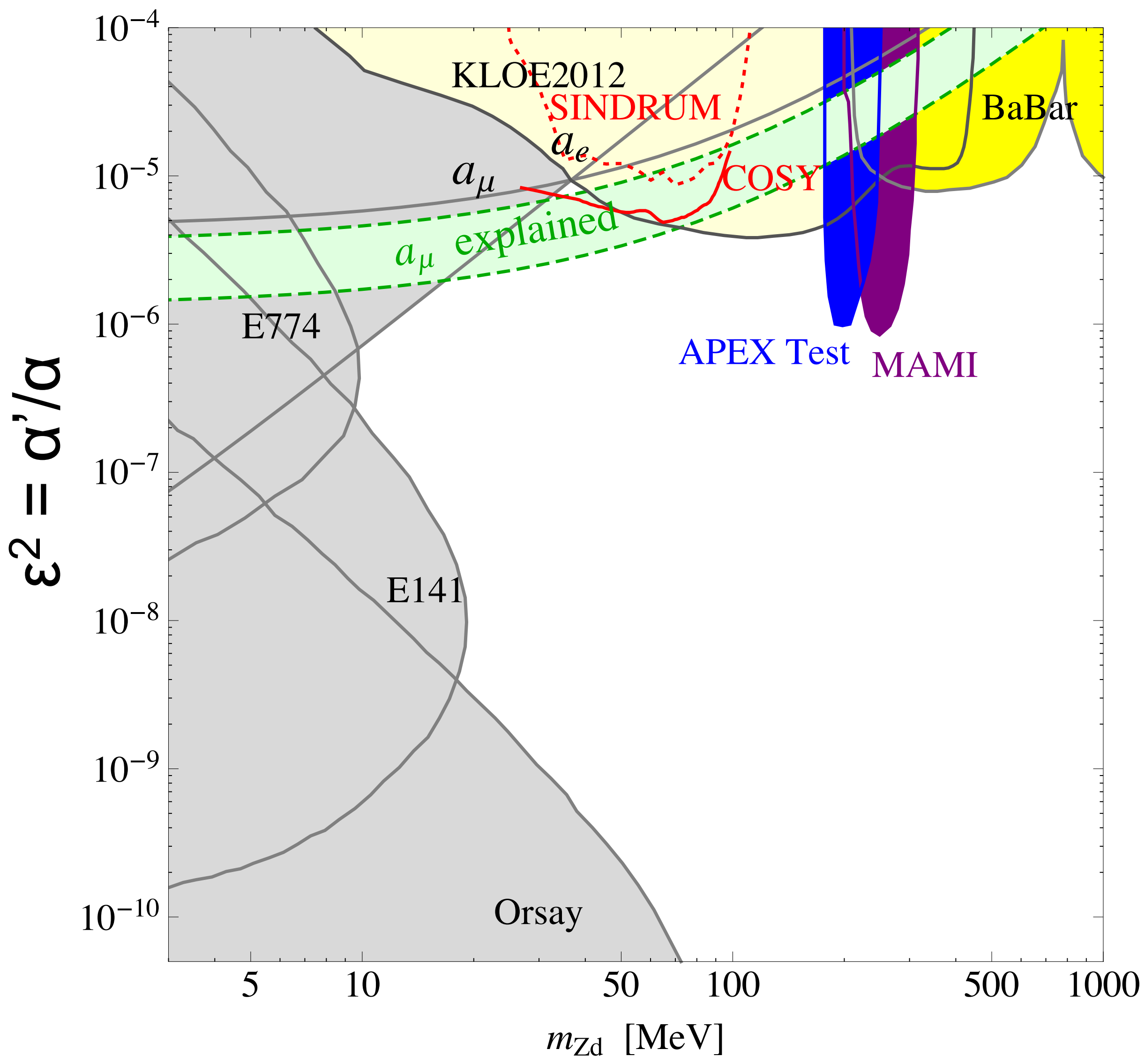
for 1 Higgs doublet + singlet

$$J^{NC}_{\mu} = \left(\frac{1}{2}T_{3f} - Q_f\sin^2\theta_W\right)\bar{f}\gamma_{\mu}f - \left(\frac{1}{2}T_{3f}\right)\bar{f}\gamma_{\mu}\gamma_5 f$$

Dark Force couplings depend on Higgs sector.

(We will use this observation to introduce "Dark Z" which couples to NC.)

Dark Photon Searches



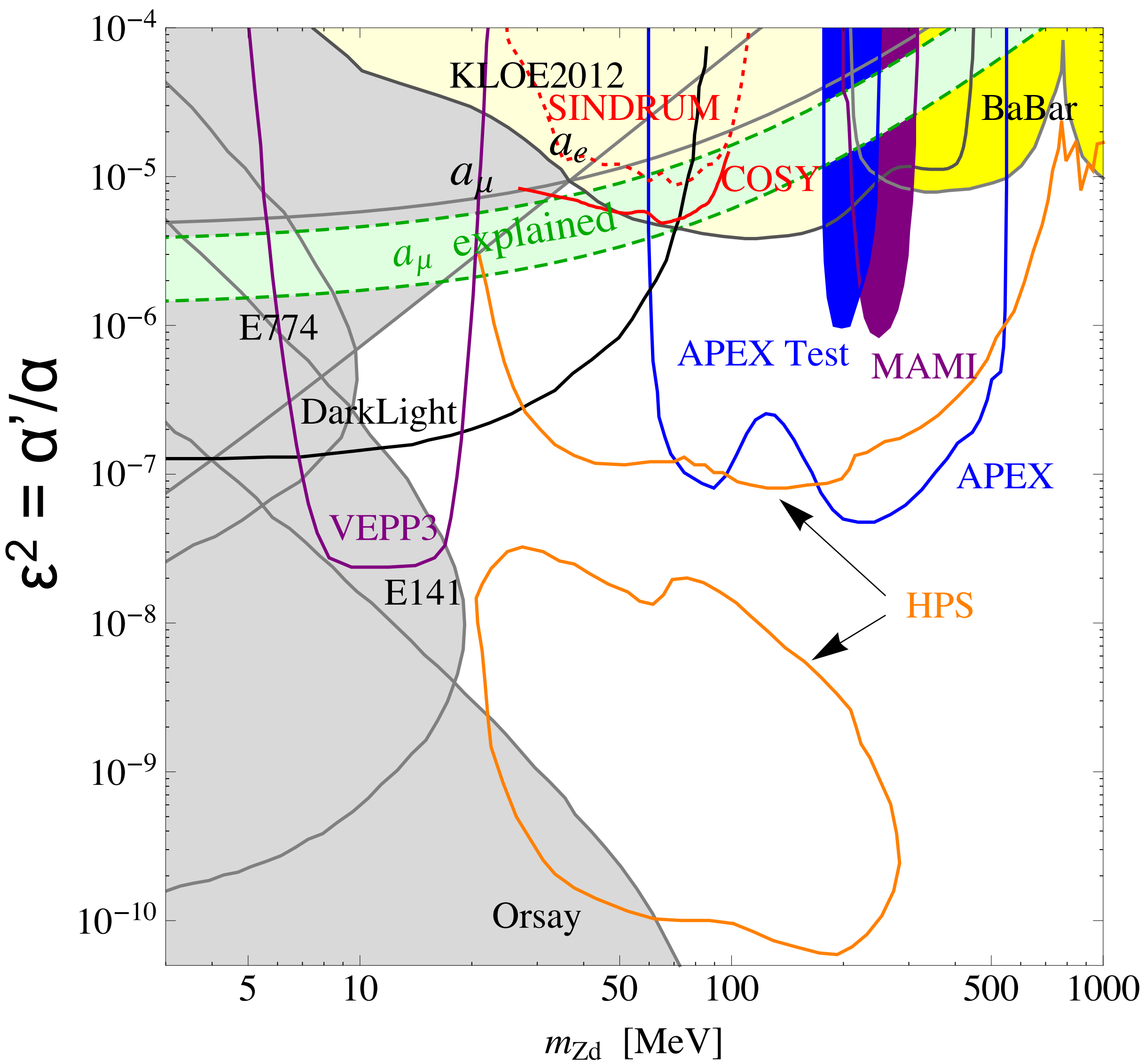
Numerous studies of Dark Photon phenomenology

[Pospelov,Ritz (2008)]
[Reece,Wang (2009)]
[Bjorken,Essig,Schuster,Toro (2009)]
[Freytsis,Ovanesyan,Thaler (2009)]
and many more ...

Current and Future coverage in the ($m_{Z'}$, ε^2) plane

1. g-2 (for e, μ). [green band: explains g_μ - 2 anomaly]
2. Beam-dump experiments (E137, E141 at SLAC; E774 at Fermilab)
3. Meson decays: ϒ(bb) ➞ ɣ Z' (BaBar); ϕ(ss) ➞ η Z' (KLOE); π(dd) ➞ ɣ Z' (COSY)
4. Fixed target experiments: New experiments designed for direct Dark Photon search (APEX, HPS, DarkLight, MAMI, VEPP3)

Dark Photon Searches

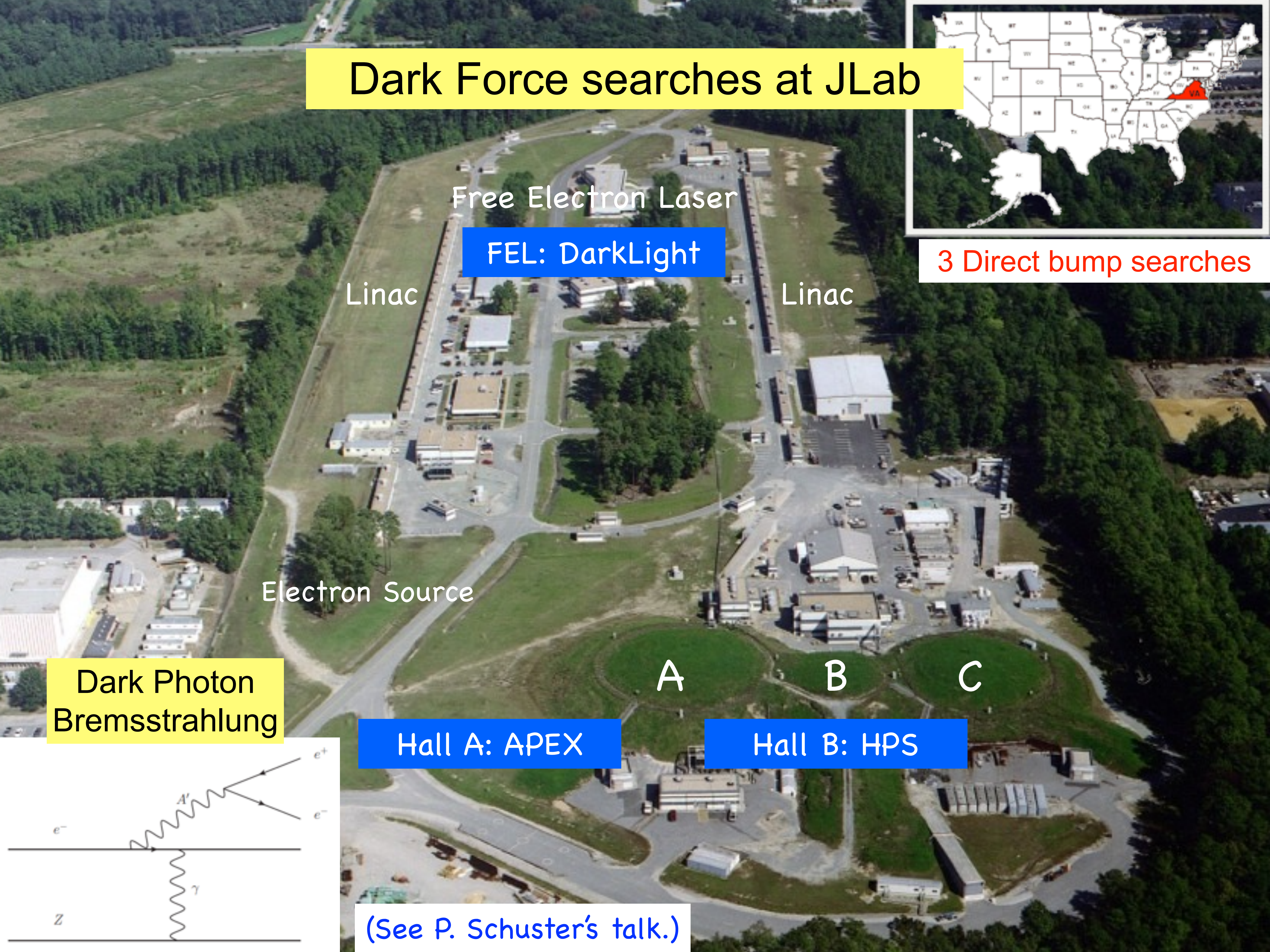


Numerous studies of Dark Photon phenomenology

[Pospelov,Ritz (2008)]
[Reece,Wang (2009)]
[Bjorken,Essig,Schuster,Toro (2009)]
[Freytsis,Ovanesyan,Thaler (2009)]
and many more ...

Current and Future coverage in the ($m_{Z'}$, ε^2) plane

1. g-2 (for e, μ). [green band: explains $g_\mu - 2$ anomaly]
2. Beam-dump experiments (E137, E141 at SLAC; E774 at Fermilab)
3. Meson decays: ϒ(bb) → γ Z' (BaBar); ϕ(ss) → η Z' (KLOE); π(dd) → γ Z' (COSY)
4. Fixed target experiments: New experiments designed for direct Dark Photon search (APEX, HPS, DarkLight, MAMI, VEPP3)


Dark Force searches at JLab
3 Direct bump searches
Free Electron Laser
FEL: DarkLight
Linac
Linac
Electron Source
A
B
C
Hall A: APEX
Hall B: HPS
Dark Photon Bremsstrahlung
e^+
A'
e^-
e^-
γ
Z
(See P. Schuster's talk.)

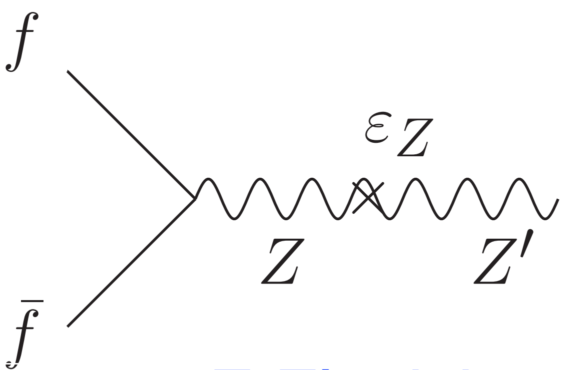
2. Dark Z
: a variant of Dark Photon with “axial coupling”

General Higgs sector

<u>Dark Photon vs. Dark Z</u>
Common part: $U(1)_Y$ & U(1)' kinetic mixing
Different part: simplest vs. more general Higgs sector

Now, Z-Z' mixing angle does not vanish in general. $\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta$

(δ : small model-dependent quantity)



Z-Z' mixing

We do not need to specify Higgs sector, but it can be realized with 2HDM (Type I):

H_1 → SM Higgs doublet
H_2 [with nonzero U(1)' charge] → gives mass to Z'
(+ optional Higgs singlet H_d)

$$\delta = \sin\beta \sin\beta_d \quad (\text{with } \tan\beta \equiv v_2/v_1 \ , \ \tan\beta_d \equiv v_2/v_d)$$

(δ is a function of vacuum expectation values.)

Dark Z

The Z' couples to EM Current (∝ ε: Photon-Z' mixing) as well as the weak Neutral Current (∝ ε_Z: Z-Z' mixing).

[ɣ, Z] $\mathcal{L}_{\rm int}^{\rm SM} = -eJ^{\mu}_{em}A_{\mu} - (g/\cos\theta_W)J^{\mu}_{NC}Z_{\mu}$

[Dark Z] $\mathcal{L}_{\rm int}^{Z'} = -\left[\varepsilon\, eJ^{\mu}_{em} + \varepsilon_Z\,(g/\cos\theta_W)J^{\mu}_{NC}\right] Z'_{\mu}$ $\quad (\varepsilon_Z = \delta\; m_{Z'}/m_Z)$

(coupling) = ε (Photon coupling) + ε_Z (Z coupling) : a combination of Photon and Z couplings

To emphasize the difference from Dark Photon (with only Photon coupling), we refer our Z' to "**Dark Z boson**". (In ε→0 limit, only Z coupling)

New axial coupling bring new properties (Parity Violation, Enhancement for boosted Z', ...), which are inherited from Z boson.

In a rough sense, (Dark Photon) ≈ Heavy-version Photon,
(Dark Z) ≈ Light-version Z.

3. Dark Z Implications for Parity-Violating Experiments

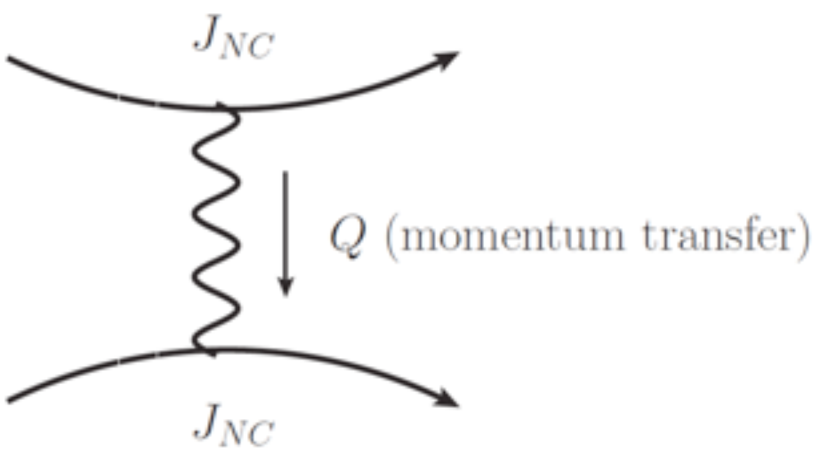
Dark Z effects on Neutral Current phenomenology

Dark Z effect comes as **modification** of effective Lagrangian of Z-mediated scattering.

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} J^{\mu}_{NC}(\sin^2\theta_W) J^{NC}_{\mu}(\sin^2\theta_W)$$

$$G_F \to \left(1 + \delta^2 \frac{1}{1 + Q^2/m^2_{Z'}}\right) G_F$$

$$\sin^2\theta_W \to \left(1 - \varepsilon\delta \frac{m_Z}{m_{Z'}} \frac{\cos\theta_W}{\sin\theta_W} \frac{1}{1 + Q^2/m^2_{Z'}}\right) \sin^2\theta_W$$

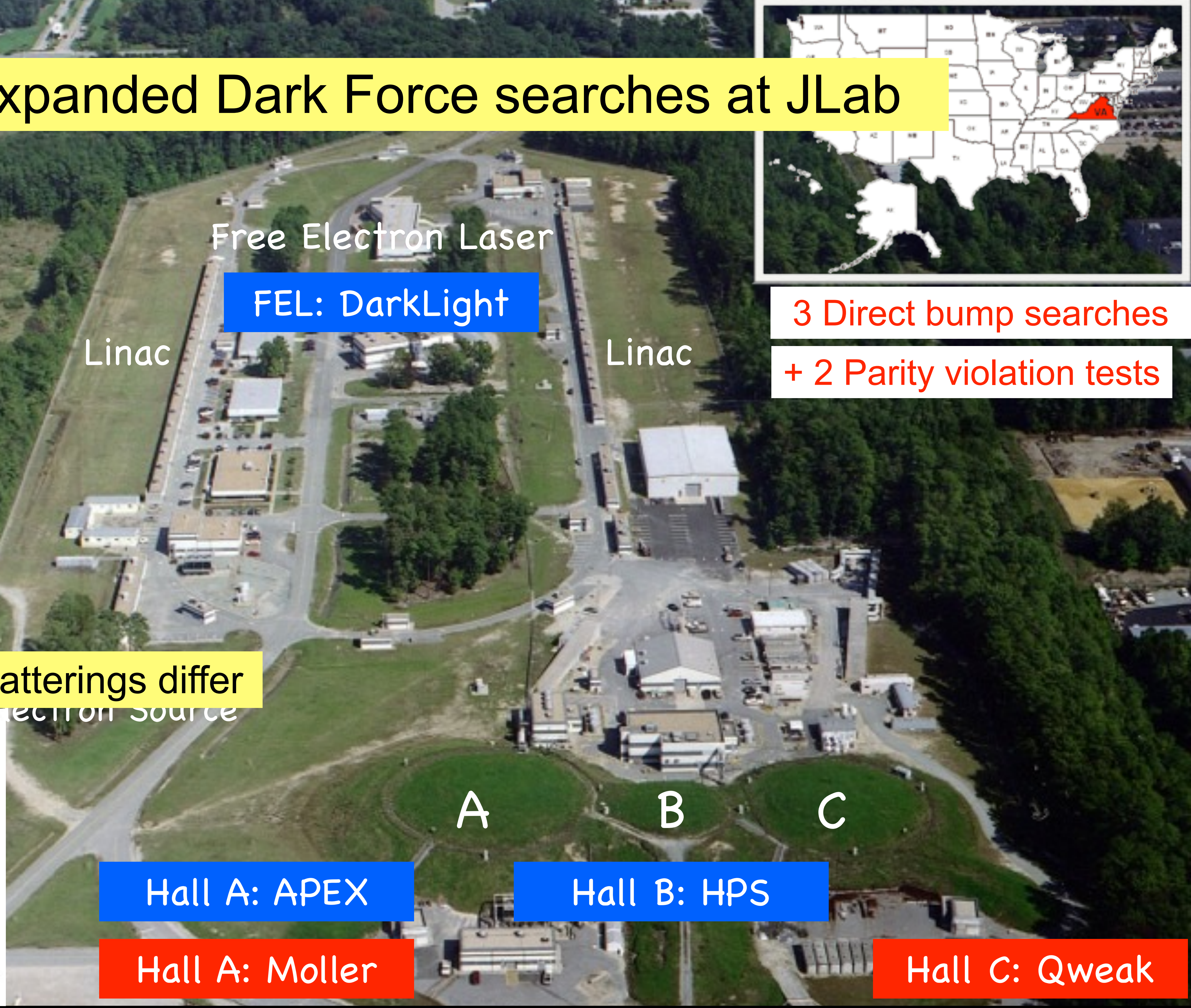


1. Sensitive only to Low-Q^2 (momentum transfer). (Effect negligible for $Q^2 \gg m_{Z'}^2$)
2. Unless ε is extremely small, $\Delta\sin^2\theta_W$ (Weinberg angle shift) is more sensitive.

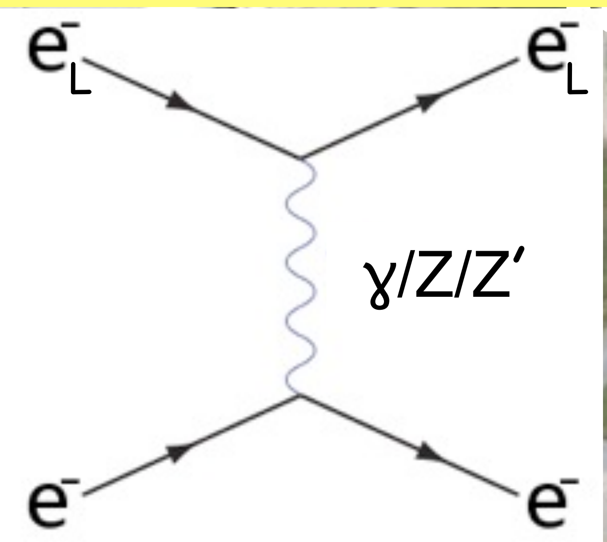
"Low-Q^2 Parity-Violating experiments (measuring Weinberg angle)" seem to be a right place to look: (i) Atomic parity violation, (ii) Polarized electron scattering.

Scattering mediated by Dark Force (Light Z') can be observed only in Low-Energy experiments.

Expanded Dark Force searches at JLab

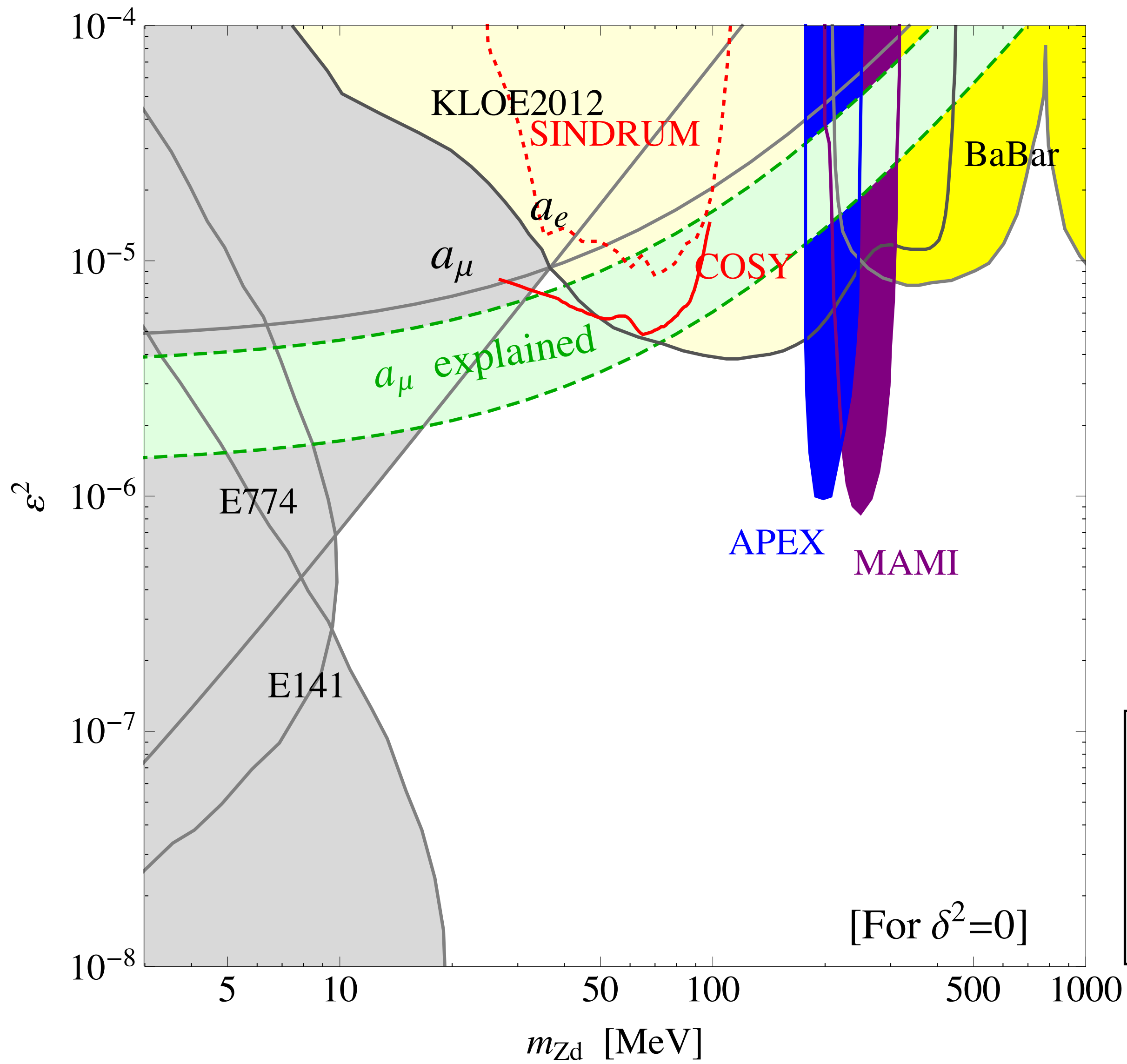


L/R polarized e-scatterings differ



Low-Q^2 Parity-Violating experiments are Complementary "Dark Force" (with axial couplings) searches!

APV and Polarized Electron Scattering



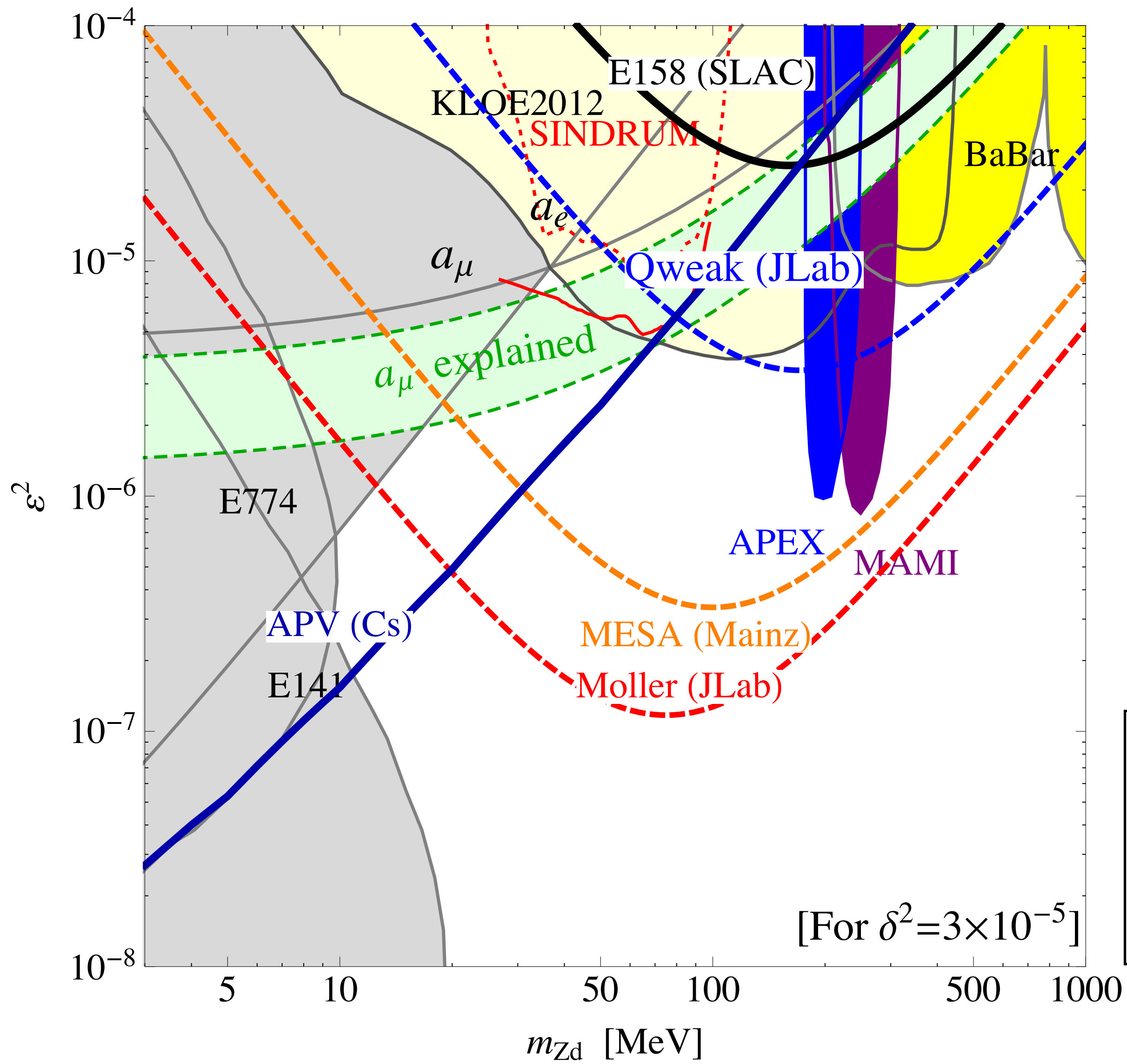
Larger δ^2 increases PV experiments coverage. (Curves in 90% CL)

$$\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta$$

If Dark Z causes muon g-2 anomaly, Qweak (at JLab) $\sin^2\theta_W$ should be in good agreement with the SM prediction. (APV closes the green band at $\delta^2 = 3\times10^{-5}$.)
In other words, if Qweak sees a significant deviation, it can “rule out” the Dark Z explanation of muon g-2 anomaly.

Future experiments (Moller, MESA) will cover more parameter space.

APV and Polarized Electron Scattering



Larger δ^2 increases
PV experiments coverage.
(Curves in 90% CL)

$$\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta$$

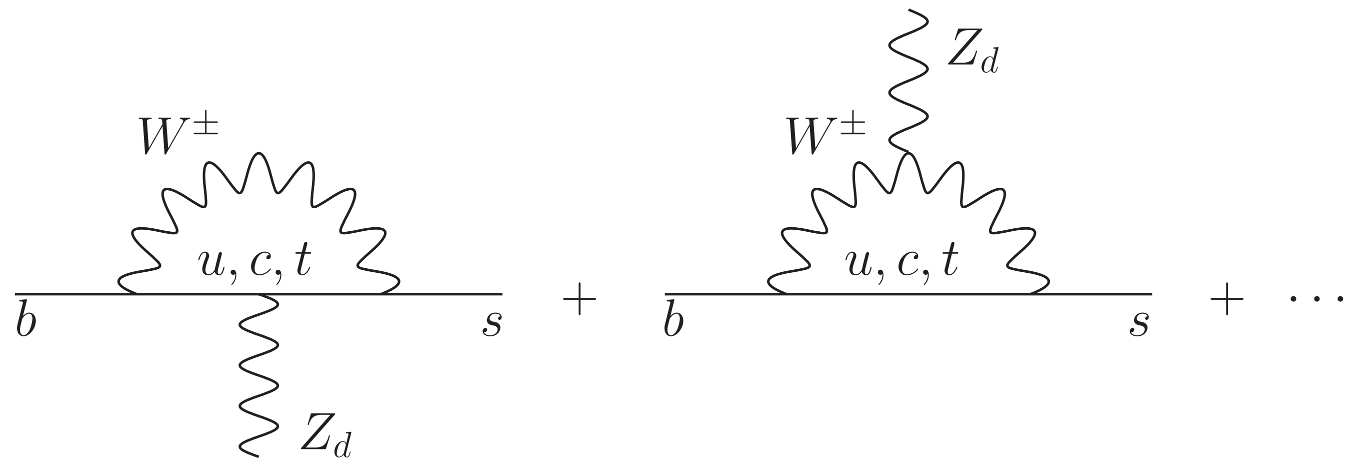
If Dark Z causes muon g-2 anomaly, Qweak (at JLab) $\sin^2\theta_W$ should be in good agreement with the SM prediction. (APV closes the green band at $\delta^2 = 3\times10^{-5}$.)
In other words, if Qweak sees a significant deviation, it can “rule out” the Dark Z explanation of muon g-2 anomaly.

Future experiments (Moller, MESA) will cover more parameter space.

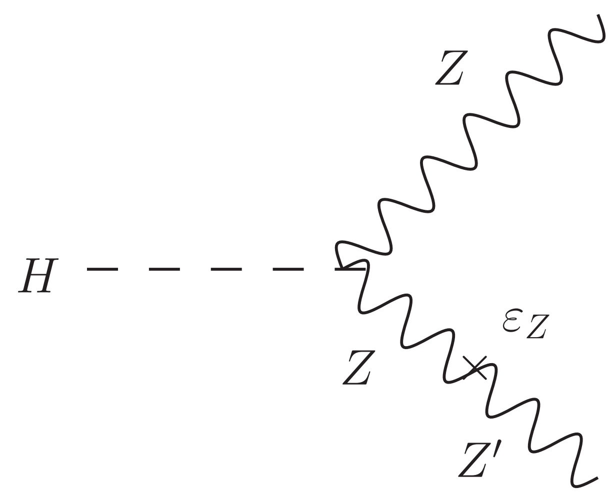
4. Dark Z Implications for Rare Meson/Higgs Decays

2-body decays into Dark Z
(Flavor-changing Meson decays & Higgs decays)

B → K Z' decay



H → Z Z' decay



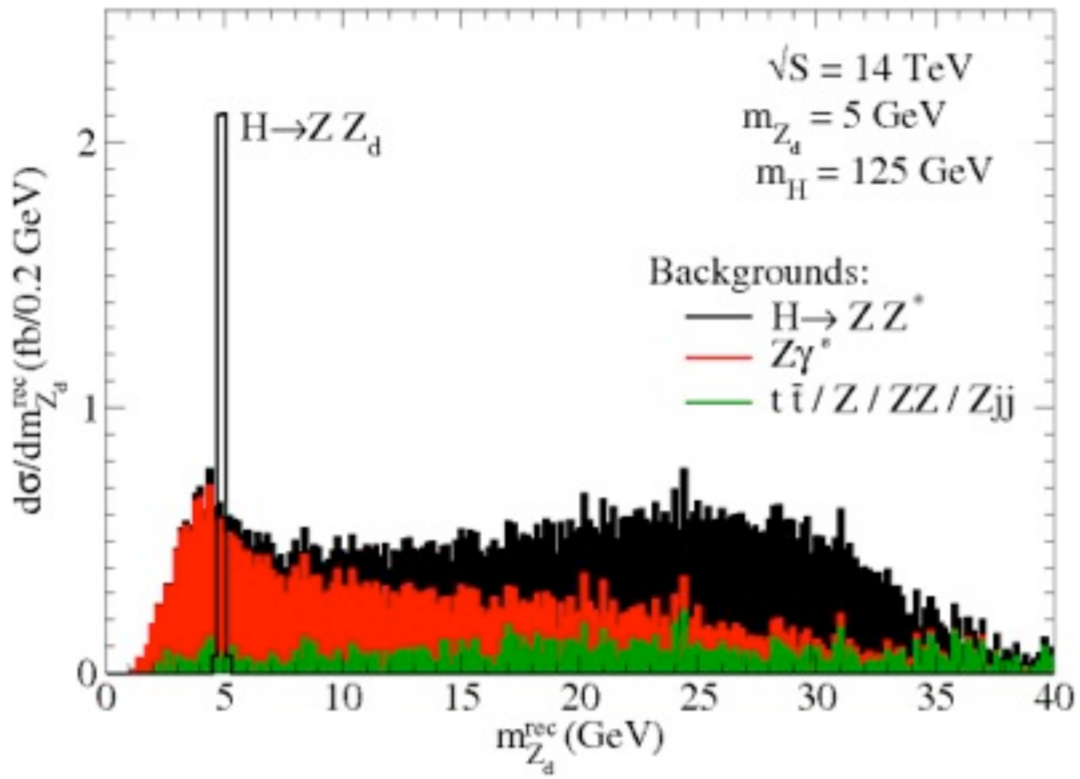
- We can expect enhanced FCNC meson decays (B → K Z', K → π Z', etc.).

Boosted gauge boson ($m_{Z'} << m_B$) behaves as Imaginary part of Higgs (Goldstone Boson Equivalence Theorem). --> It couples strongly to top-quark in loop.

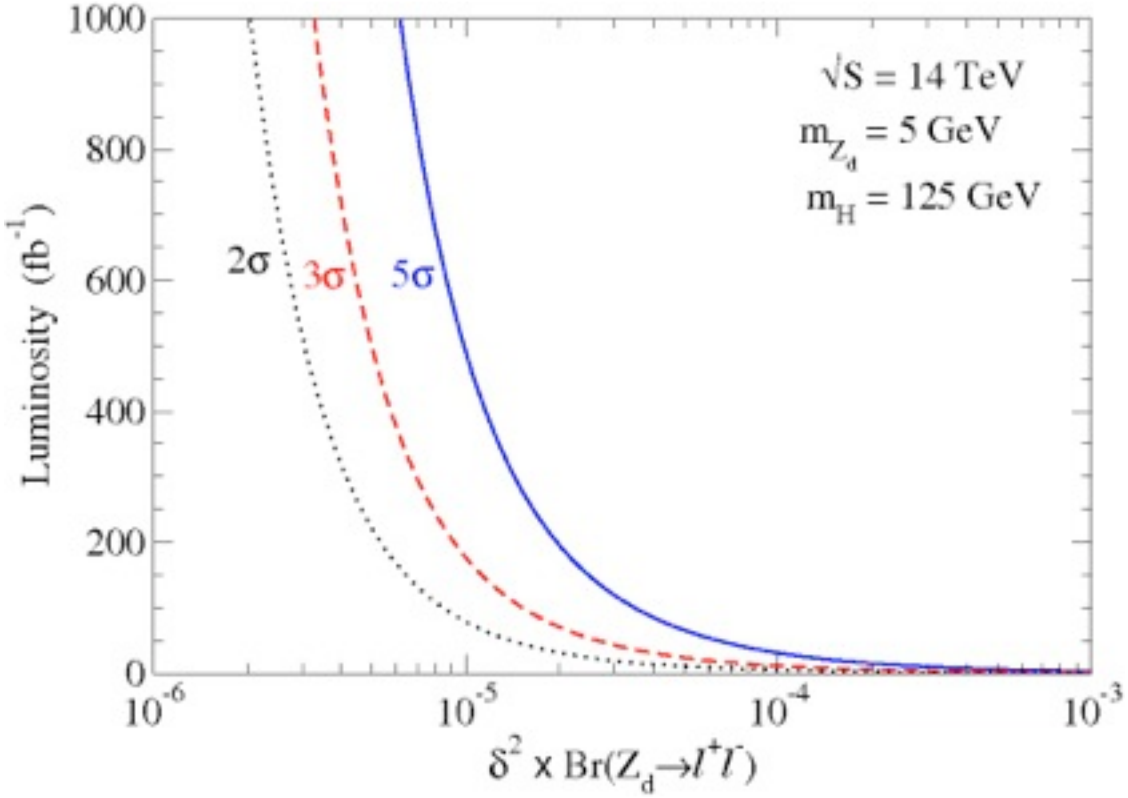
- Similarly, H → Z Z' decay is sizable and observable at the LHC.

Dark Z search at LHC experiments (Higgs → Z Z' → Z + ll)

Expect a "spike" in low invariant mass



[Dilepton Invariant Mass]



[Discovery reach at LHC]

Typical Z + 2lepton search at ATLAS/CMS [H → Z $Z^{(*)}$]: Impose $M_{\ell\ell} \gtrsim$ 15-20 GeV to reduce BKG (such as Zγ^*).

But "$M_{\ell\ell}$ ~ several (5-10) GeV" could be a sweet spot for Dark Z bump hunt at LHC (few × 100 fb^{-1} for discovery).

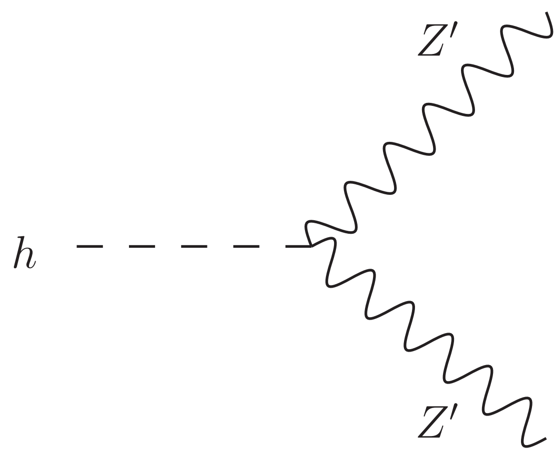
For lower mass ($m_{Z'} \lesssim$ 5 GeV), the LHC may not be sensitive, but Low-Energy experiments (JLab, B-factory, ...) can search for them.

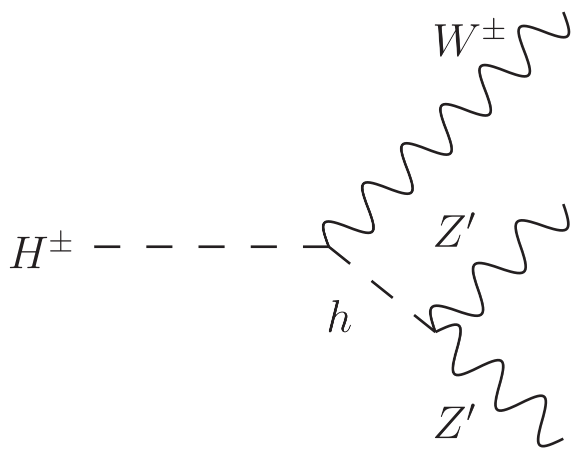
Rare Higgs decays are Complementary (sensitive to different mass range) **to Dark force searches at Low-E experiments (JLab, B-factory).**

Other Higgses in 2HDM realizations

If Dark Z (requiring more general Higgs sector) is realized in 2HDM (Dark 2HDM), there are other Higgses: h, $H^{\pm}$

Their dominant decay modes can be completely different from typical 2HDMs.





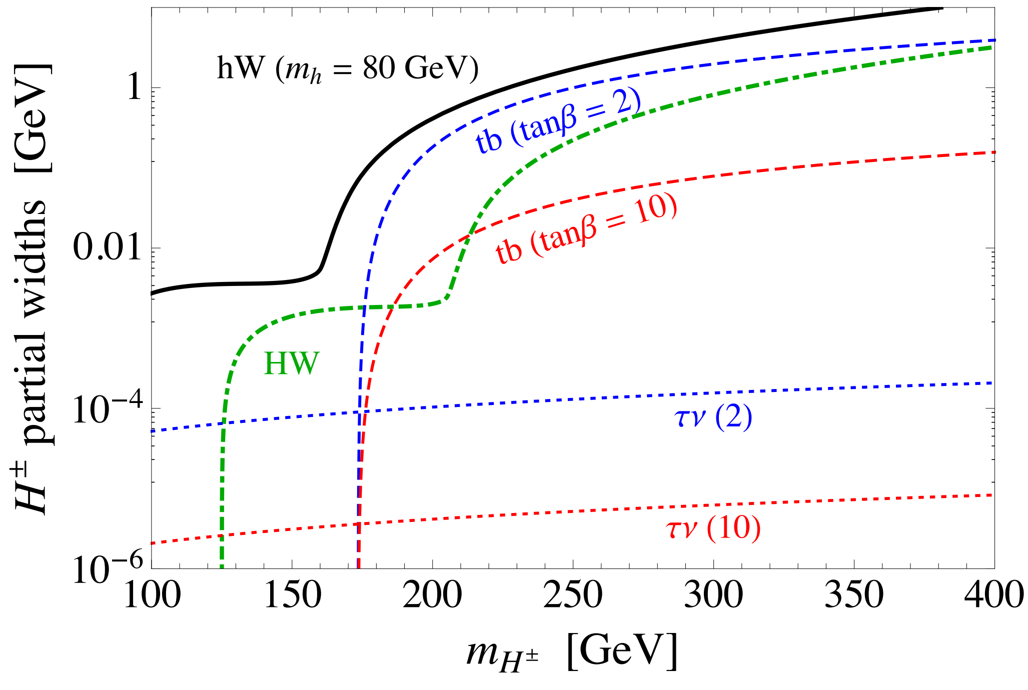
Dominant decay modes (in sizable parameter-region):

h (say, 60-90 GeV) → Z' Z'

$H^{\pm}$ → h $W^{\pm}$ → Z' Z' $W^{\pm}$

with BR(Z' → ℓ ℓ) ≈ O(0.1)

Conventional searches for 2HDMs would not find them. (Again, leptons are important signals.)



Summary

"Dark Z" model expands the Dark Force searches

In this talk,
(i) We generalized the "Dark Photon" to "Dark Z".
(ii) We expanded the relevant Dark Force search experiments.

With $U(1)_Y$ & $U(1)'$ kinetic mixing, Z' coupling depends on details of Higgs sector.
(i) **Dark Photon:** couples to EM Current (simplest Higgs sector)
(ii) **Dark Z:** couples to Neutral Current as well (more general Higgs sector)
Dark Z is a natural way to introduce "axial couplings" to "Dark Photon"-like study.

Associated Phenomenology:
(i) Low-Q^2 parity violation (ex. Polarized electron scatterings at JLab, Mainz)
(ii) Low-E bump searches (ex. $B \to K Z'$ for $m_{Z'} \lesssim 5$ GeV)
(iii) High-E bump searches (ex. $H \to Z Z'$ for $m_{Z'} \approx 5$-10 GeV)

Prospect of Dark Force is Bright.
(With it, New physics discovery may come from many different types of experiments.)

- Thank you. -

Backup Slides

Bounds on δ

$$\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta$$

Process	Current (future) bound on δ	Comment
Low Energy Parity Violation	$\lvert\delta\rvert \lesssim 0.08 - 0.01$ (0.001)	Fairly independent of m_{Z_d}. Depends on ε.
Rare K Decays	$\lvert\delta\rvert \lesssim 0.01 - 0.001$ (0.0003)	$m_\pi^2 < m_{Z_d}^2 \ll m_K^2$. Depends on BR$(Z_d)$.
Rare B Decays	$\lvert\delta\rvert \lesssim 0.02 - 0.001$ (0.0003)	$m_\pi^2 < m_{Z_d}^2 \ll m_B^2$. Depends on BR$(Z_d)$. Some mass gap ~ 3 GeV.
$H \to ZZ_d$	$\lvert\delta\rvert \lesssim (0.003 - 0.001)$	$m_{Z_d}^2 \ll (m_H - m_Z)^2$. Depends on BR$(Z_d)$ and background.

TABLE II: Rough ranges of current (future) constraints on δ from various processes examined along with commentary on applicability of the bounds. These processes have negligible sensitivity to pure kinetic mixing effects.

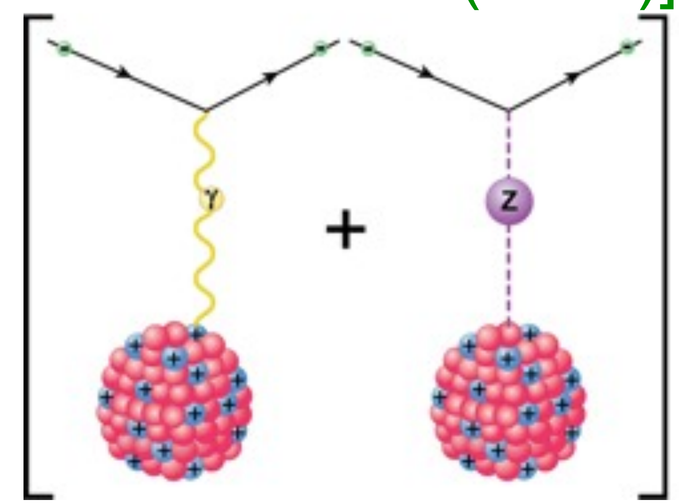
Low-Q^2 Parity-Violating Experiments

Atomic Parity Violation [Weak nuclear charge $Q_W(Z,N) \simeq -N+Z(1-4\sin^2\theta_W)$]:

$Q_W(^{133}Cs) = -72.58(43)$ in Cesium Experiment [C. Wieman et al (1985-1988)]

$Q_W(^{133}Cs) = -73.23(2)$ in SM [reflecting new result by Flambaum et al (2012)]

in a reasonable agreement (1.5σ).

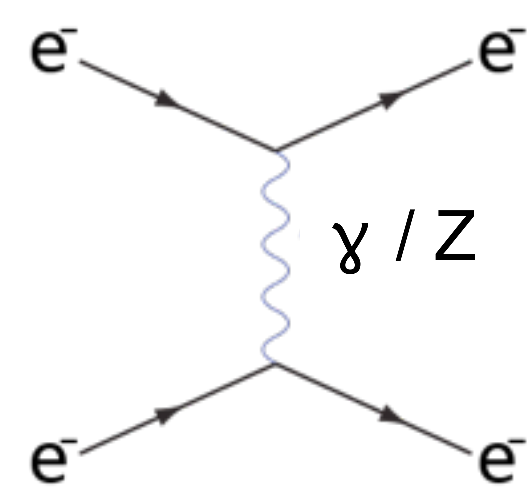


Polarized Electron Scattering [Left-Right asymmetry $A_{LR} = \sigma_L-\sigma_R / \sigma_L+\sigma_R$]:

$\sin^2\theta_W(m_Z)=0.2329(13)$ SLAC E158 (e^-e^- Moller scattering; $Q\approx160$ MeV) (2005)

$\sin^2\theta_W(m_Z)=0.23125(16)$ at Z-pole average (LEP, SLC)

in good agreement.



$$\Delta \sin^2\theta_W \simeq -0.42\varepsilon\delta\frac{m_Z}{m_{Z'}}f(Q^2/m_{Z'}^2)$$

Flavor-changing Rare meson decays into Light Z’ ($B \to K Z'$, $K \to \pi Z'$)

Sufficiently light Dark Z (for $m_{Z'} \ll m_B$) can be boosted.

[Dark Z] $$\mathrm{BR}(B \to K Z')|_{\mathrm{longitudinal}} \simeq 0.1\,\delta^2$$

[Boosted gauge boson is longitudinally polarized, and it behaves as Imaginary part of Higgs (Goldstone Boson Equivalence Theorem). It couples strongly to heavy particles.]

Compare this to Dark Photon case (typically, $|\varepsilon| \lesssim 10^{-3}$).

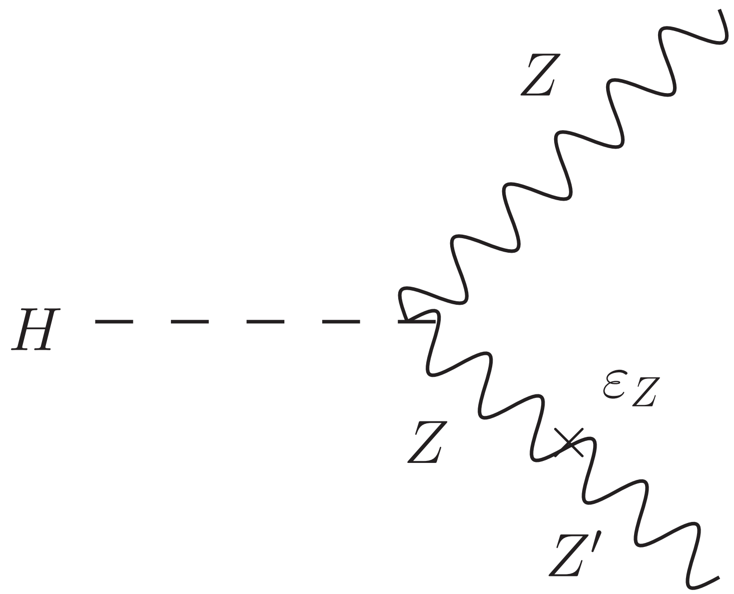
[Dark Photon] $$\mathrm{BR}(B \to K Z') \sim 6 \times 10^{-7}\,\varepsilon^2 \quad (\text{for } m_{Z'} \simeq 1 \text{ GeV})$$

[Batell, Pospelov, Ritz (2009)]

[No GBET enhancement because its longitudinal mode does not contain SM Higgs doublet.]

SM-like Higgs (125 GeV) → Z Z'
(Connection of High-E and Low-E physics)

SM-like Higgs (mass ~ 125 GeV) was discovered at LHC experiments.
(It is about time to do precision Higgs study).



[Dark Z] (HZZ' coupling) = ε_Z (HZZ coupling)

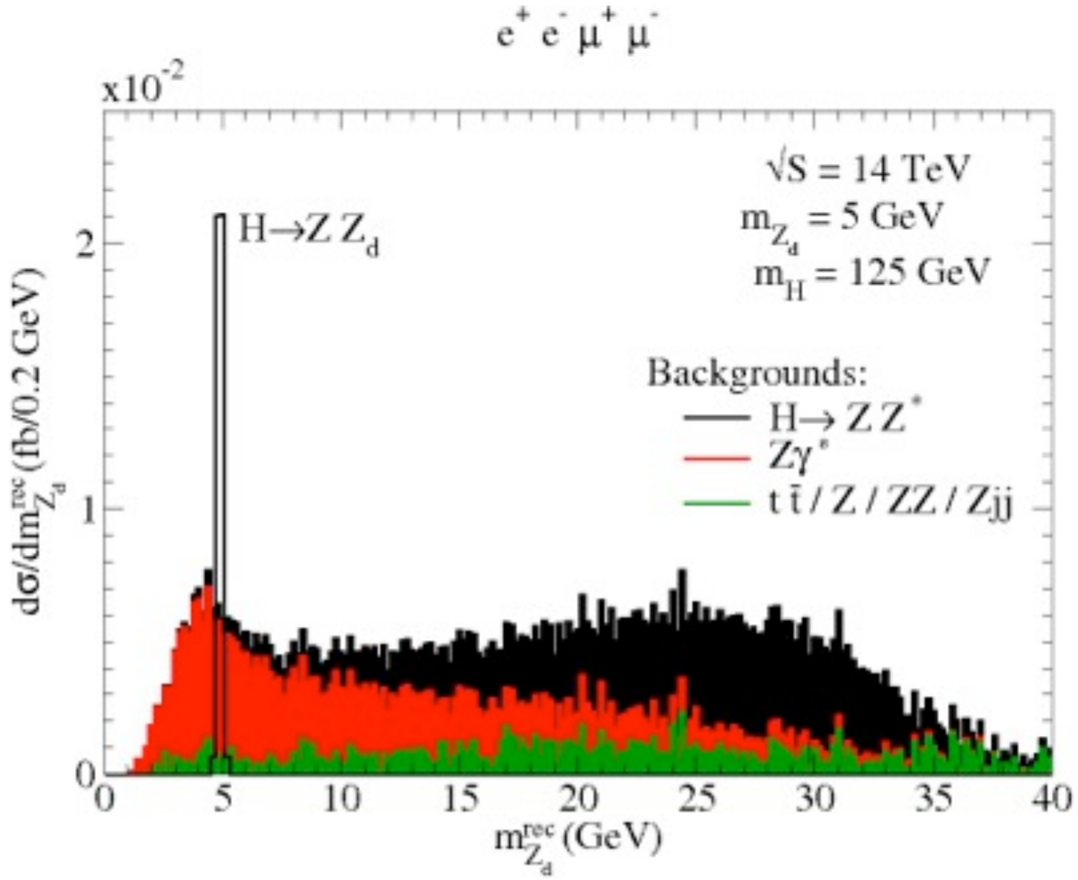
[Dark Photon] (HZZ' coupling) = loop-suppressed

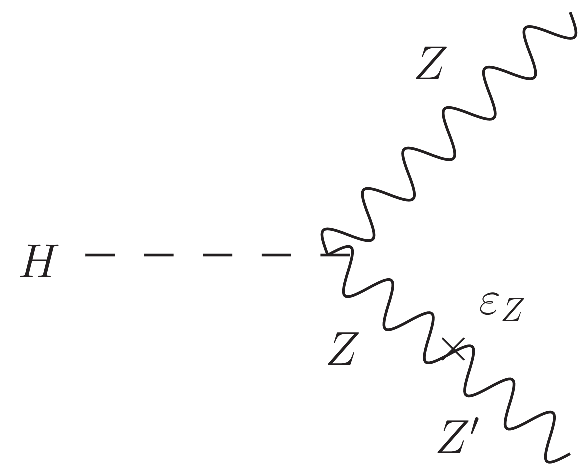
Also GBET provides an enhancement for boosted Z'.
SM example: [Higgs-G-G coupling] ~ g m_H^2/m_Z vs. [Higgs-V-V coupling] ~ g m_Z

For $m_{Z_d}^2 \ll D^2$ (with $D^2 \equiv m_H^2 - m_Z^2$), we have

$$\begin{aligned}\Gamma(H \to Z Z_d) &= 4\pi \frac{\sqrt{\lambda(m_H^2, m_Z^2, m_{Z_d}^2)}}{64\pi^2 m_H^3} \sum_{\text{pol}} |\mathcal{M}|^2 \\ &\simeq \frac{D^2}{16\pi m_H^3} \left(\mathcal{C}_{HZZ}^{\text{SM}}\right)^2 \left(\varepsilon_Z^2 \frac{D^4}{4 m_Z^2 m_{Z_d}^2} + 3\varepsilon_Z \kappa_Z \frac{D^2}{m_Z^2} + \kappa_Z^2 \frac{D^4}{2 m_Z^4} + \tilde{\kappa}_Z^2 \frac{D^4}{2 m_Z^4} \right)\end{aligned}$$

Cuts in SM-like Higgs (125 GeV) → Z Z' → 4-leptons





$$m_{12}^2 = 2E_1E_2(1 - \cos\theta_{12})$$

$p_T^\ell > 4$ GeV

ATLAS trigger for $H \to ZZ^*$ (one $p_T^\ell > 24$ GeV or two $p_T > 13$ GeV)

$|\eta^\ell| < 2.5$

$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.3$

$|m_{4\ell} - m_H| < 2$ GeV

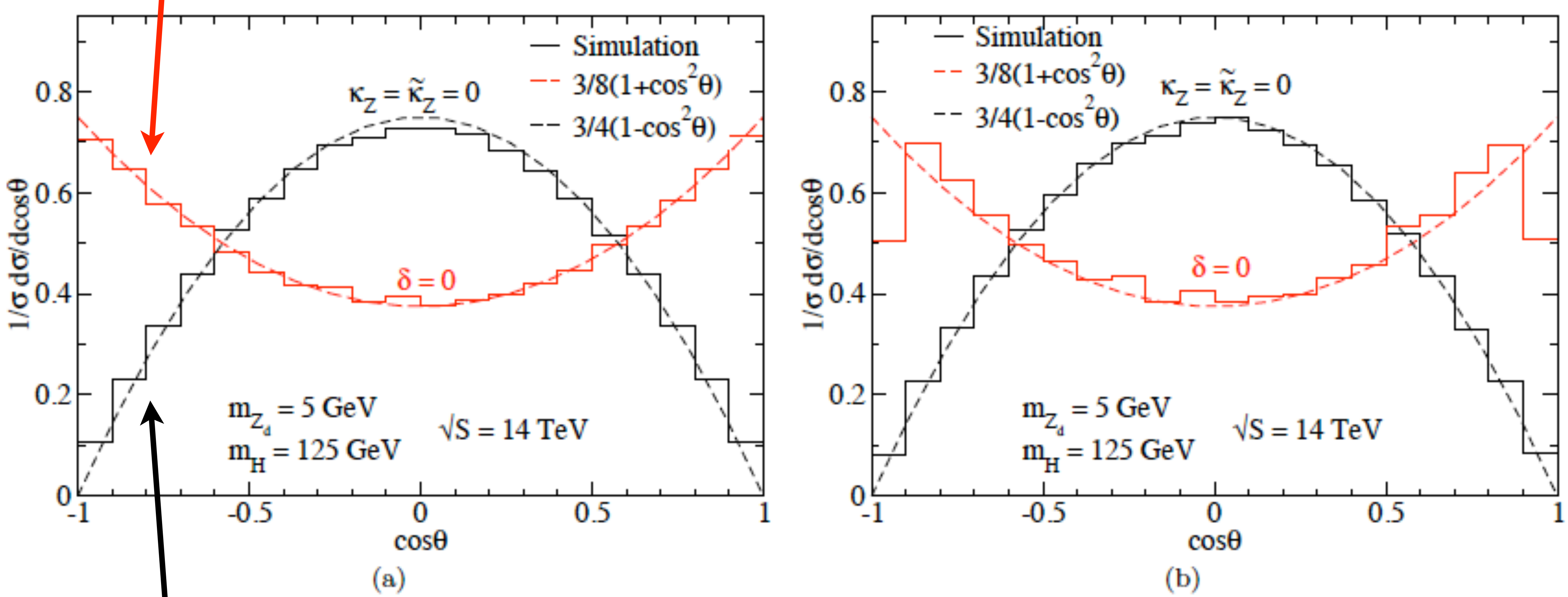
$|m_Z^{\text{rec}} - m_Z| < 15$ GeV

	$m_{Z_d} = 5$ GeV		
	2σ (Excl.)	3σ (Obs.)	5σ (Disc.)
No K-factors	78 fb^{-1}	180 fb^{-1}	490 fb^{-1}
$+K$-factors	33 fb^{-1}	75 fb^{-1}	210 fb^{-1}

	$m_{Z_d} = 10$ GeV		
	2σ (Excl.)	3σ (Obs.)	5σ (Disc.)
No K-factors	100 fb^{-1}	230 fb^{-1}	640 fb^{-1}
$+K$-factors	42 fb^{-1}	95 fb^{-1}	260 fb^{-1}

Angular Distribution of Lepton from H → Z Z'

Transversely polarized Z'



Longitudinally polarized Z'
("Dark Z" type)